ULTRADISPERSION MICROSTRUCTURE AND PHASE COMPOSITION FORMATION DURING INTENSIVE METAL FORMING

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Abstract

It was shown in this paper how rate, speed and temperature of forming influence on core size, as well as influence of the cooling speed on phase composition of construction steels. Different ways of intensive deformation achievement during metal forming and in particular a flat shaped condition: equal channel angular extrusion, drawing, cross-rolling, are considered in this paper. It should be also noted that for the receipt of the required structure and mechanical properties of steel apart from the use of rational speed-temperature process parameters of forming a metal damage limit should be taken into account.

In 1977 V.M.Segal received patent of the USSR for the deformation method at equal channel angular extrusion of blank part. (Figure 1) [1]. The idea of realization of significant deformation without shape change of the stock material appeared attractive. The author asserted, that in such a way it was possible to receive quickly a fine-grained structure even in that case when the stock material was an ingot with a rough dendrite structure.

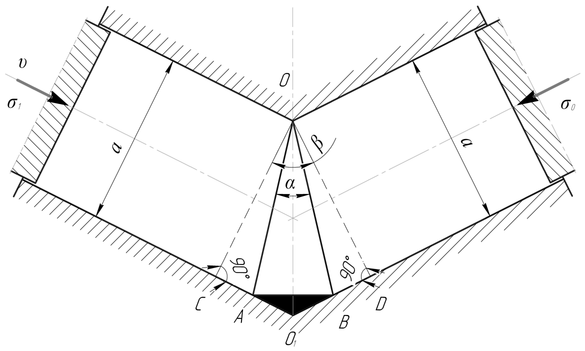


Fig. 1.Scheme of equal channel angular extrusion with counter-pressure ($\sigma_1 > \sigma_2$)

The majority of followers of V.M.Segal count intensive plastic deformation at equal channel angular extrusion a principal cause of core shallow and do not consider processes of change of dislocation and grain structure of metal at recrystallization. J.M.Vainblat showed, that exactly temperature-speed conditions of deformation and not a deformation ratio made a crucial influence on evolution of the grain structure. He developed the phenomenological model and methods of construction of the diagram of the structural condition of alloys (fig. 2) [2,3].

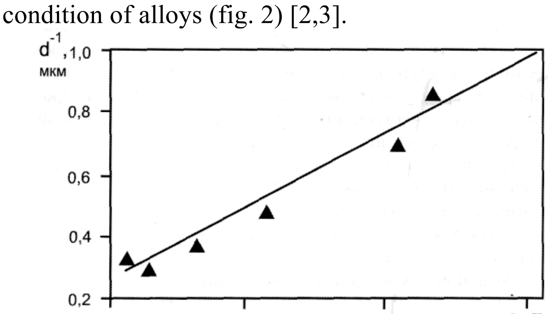


Fig. 2. Dependence of subgrain size from Zener-Kholomon parameter for aluminum alloy [3]

At that he used a concept about equilibrium process of deformation for which the energy of plastic deformation reserved by a crystalline lattice was characterized by Zener-Kholomon parameter $z = \xi_u \exp(Q / R\theta)$ where Q was an activation energy describing relaxation process, ξ_u and ξ - intensity of a strain rate and temperature. Besides it was shown, that for the majority of processes of metal forming $\lg z >$ 10, and linear dependence $\lg z = \lg A + \frac{\beta}{2,3}\sigma_S$ [5, 7, 8] was fair. The reserved energy of plastic deformation can be characterized by the total area of subboundaries in the unit of volume and is considered to be inversely proportional to an average diameter of a subgrain *d*. It is proved by experimental data (fig. 3).

The diagram of a structural state can be conditionally divided into four areas related to various types of an alloy structure after deformation and heat treatment: 1 - generated after a dynamic recrystallization and kept after heat treatment; 2 - formed at a static recrystallization in a course of post-deformation anneal; 3 - mixed structure; 4 - received in a result of metadynamic or spontaneous recrystallization characterized by formation of polygonized substructure with high angle disturbance on subboundaries.

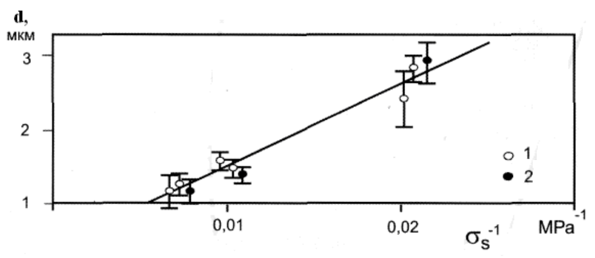


Fig. 3. Dependence of subgrain size of austenitic steels (1) and (2) from deformation stress on steady-state stage of hot deformation at θ 1050° C [4]

Any structure is formed during high-speed deformation and recrystallization during cooling-down of ingot after deformation process. Using the diagram of a structural condition, it is possible to choose rational temperature-speed schedules for deformation process with the purpose of achievement of the required core size, and after heat treatment – phase composition. Practical appendices of application of the phenomenological model and structural condition diagrams for the development technological processes have been considered in works [7-10].

It is important to note, that in order to receive a process of ultrafine-grained structure it is necessary to execute a condition of metal damage limit, using the criterion of micro-fracture at plastic deformation $\omega < \omega^*$. In accordance with theory the degree of breakdown of the material is characterized by damage limit ω. It is assumed that the value $\omega = 1$ corresponds to macroscopic crack appearance, seen with the naked eye, whereas $\omega = 0$ - initial state of the material prior to deformation [12]. Two criteria of metal micro-fracture are known: $\omega = \omega^*$ corresponds to the appearance of microscopic pores and cracks, not cured at grain recovery; $\omega = \omega^{**}$ corresponds to the appearance of micro-cavities, the size of which exceed the size of grain, that leads to the reduction of strength properties and product life. When $\omega < \omega^*$ in the result of cell formation during heating a reestablishment of dislocation arrangement in metal without loss of mechanical and processing properties is occurred, and then after recrystallization improvement of mechanical and processing properties is observed at the expense of rise of structure dispersability.

Let us consider plastic yielding of the material, forced through two crossing channels of equal cross section (Fig. 5*a*) in the condition of plain strain.

Flow of metal is occurred at the expense of stroke of compression ram 1. The exact decision of task is given by the field of slip lines and corresponding to this field the velocity hodograph, shown on figure 5a. Material areas *I* and *III* move in channels with equal speeds υ as hard ones; area AO_1B also remains hard. Plastic field *II* is formed by align sheaf, in which α-slip lines are the segments of a circle with the center in the point *O*, and β-slip lines of radius, convergent in the point *O*.

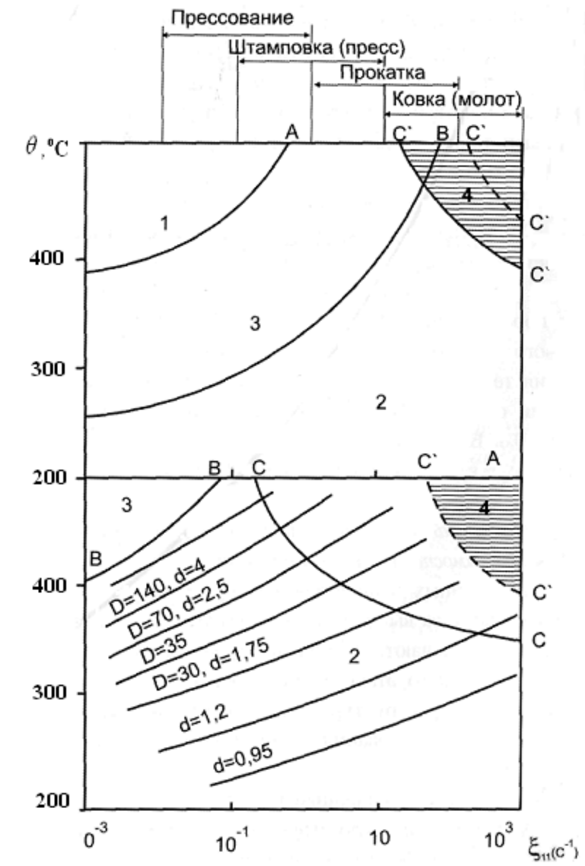
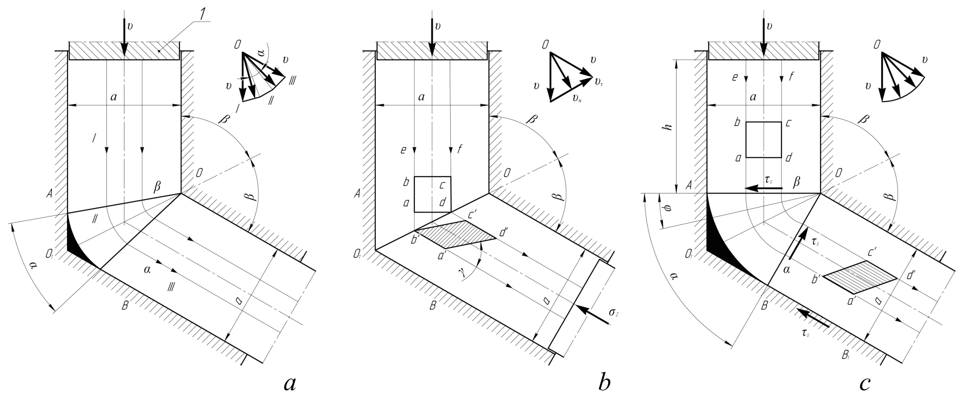


Fig. 4. Examples of structural condition diagrams:
a – alloy АК 6 (strain rate intervals for different types of metal deformation process are stated);
b – alloy АК 4-1 (thin lines – z = const, dimensions - d, D are given in mkm)



a *b* *c*

a – general case; *b* - $\tau_k = 0$; *c* - $\tau_k = \tau_s$.

Fig. 5. The scheme of equal channel extrusion

The geometry of the field is defined by the angle of turn of the align sheaf, the value of which depends on the friction conditions on the contact surface:

$$\alpha = \arccos\frac{\tau_k}{\tau_s} - 2\beta, \; \left(\frac{\tau_k}{\tau_s} > \cos 2\beta\right),$$

where τ_k - contact friction on the walls of the channel, 2β - the angle between the axis of the channels. The angle α is recommended to be defined by the method of upper rate out of the condition of deformation strength minimization [12].

For the case without friction it is obvious that stressed and strain state during equal channel extrusion is realized in endless thin field of pure shear OO_1, is homogeneous and fully defined by angle β and counter-pressure σ_2, the choice of which allows to modify process parameters in a considerably wide range.

In general case (Fig. 5*a*) strained state will be formed out of sequence of simple shears in the direction of β and $-\beta$ on the velocity lines of failure *AO* and *BO* and along α-slip lines in the area *ABO*, and full gain of shear deformation ratio

$$\Lambda = \alpha + 4ctg\left(\frac{\alpha}{2} + \beta\right).$$

Accordingly, maximum possible value of shear deformation ratio at equal channel angular extrusion is - Λ =2.

Stressed state in the general case will be as follows:

$$\sigma_{OB} = -\tau_s \cdot ctg\left(\frac{\alpha}{2}+\beta\right) + \sigma_2;$$

$$\sigma = \sigma_{AOB} = -\tau_s\left(2ctg\left(\frac{\alpha}{2}+\beta\right) + 2\alpha - 2\phi\right) - \psi\tau_s \cdot ctg\left(\frac{\alpha}{2}+\beta\right) + \sigma_2;$$

$$\sigma_1 = -\tau_s\left(4ctg\left(\frac{\alpha}{2}+\beta\right) + 2\alpha - 2\phi\right) - 2\psi\tau_s \cdot \left[ctg\left(\frac{\alpha}{2}+\beta\right) + \frac{h}{a}\right] + \sigma_2.$$

In the given formulas the friction coefficient ψ (friction is calculated by Zibel method $\tau_k = \psi\tau_s$) is expressed in terms of angles α and β:

$\psi = \cos(\alpha + 2\beta)$,

when $\psi = \frac{\tau_k}{\tau_s} > \cos 2\beta$ [12].

Thus, in the general case (Fig.5*a*) the average normal (direct) stress σ, as well as extrusion stress σ_1, is a complicated function, vary depending on several disposal variables (ψ, α, β, σ_2), geometry of the channels ($\frac{h}{a}$), and properties of the test material (τ_s).

For an evaluation of metal damage limit at equal channel angular extrusion we shall take advantage of accumulation model of metal damage limit at monotonous deformation by the following technique:

$$\omega = \int_0^{\Lambda_1} \frac{a \cdot \Lambda^{a-1}}{\Lambda_p^a} d\Lambda,$$

where $\Lambda_p = \chi \cdot \exp\left(\lambda \cdot \frac{\sigma}{T}\right)$ - dependence of metal plasticity from stressed state values at Lode value $\mu_\sigma = 0$, representative for the conditions of flat forming;

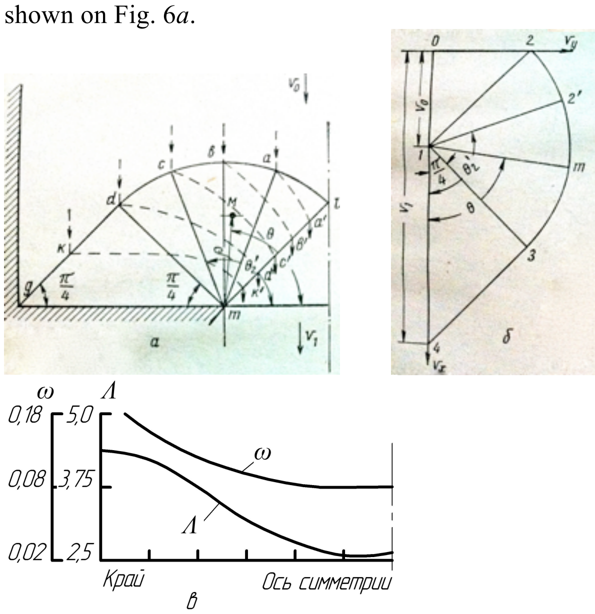
$\frac{\sigma}{T}$ - stressed state value;

$a = a_0^{1+b\cdot\frac{\sigma}{T}}$ - index, describing the change of damage limit of the material in the time interval $\tau(0,t)$;

χ, λ, b, a_0 - empirical constants of steel and alloy (they are found from tests) [12].

It should be noted that intensive deformation areas are typical not only for the process of equal channel angular extrusion. Such processes are press forming process, drawing and etc.

We shall consider process of metal press forming through the smooth container and die body [11]. The field of slip-lines at press forming with drawing λ =3 is shown on Fig. 6*a*.



a – the field of slip lines and current lines; б – velocity hodograph; в – alloy damage AMn5 (ω) and shear deformation ratio (Λ)

Fig. 6. Press forming of alloy AMn5 without friction.

Distribution of shear deformation ratio and strip gage damage limit are shown on Fig. 6*в*. The value Λ is increasing from the center of strip to the marginal fibers [11].

The scheme of drawing process of sheet (for simplicity we shall use the drawing process without friction) through slotted die body – drawing die with the angle α =15° with reduction coefficient 1,37 is shown on Fig.7.

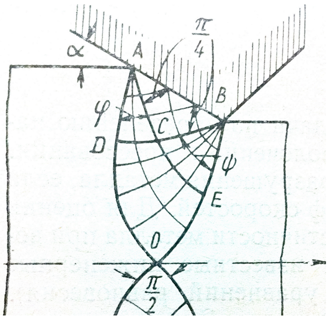


Fig. 7. The scheme of drawing process of sheet

For definition of stressed state and shear deformation ratio Λ, as well as the drawing damage limit ω, a method of slip-lines is used (solution of this task is given in [11]). The results of calculation of Λ and ω are given on Fig. 8

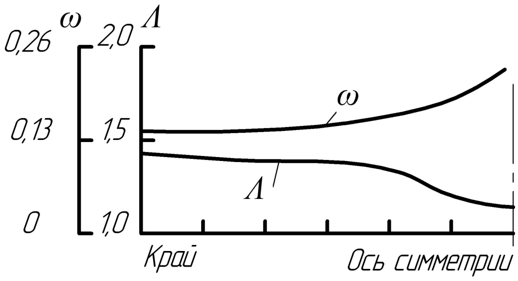


Fig. 8. Damage of steel grade 20 and shear deformation ration at drawing of sheet.

From the analysis of the considered processes of equal channel extrusion, direct extrusion, drawing of sheets it is visible, that it is possible to achieve a required deformation ratio by using of the known ways of metal forming process, which is practically much easier in comparison with process of equal channel angular extrusion. Traditional processes of metal forming are not difficult to perform with rational temperature-speed conditions of deformation and metal damage limit, providing the receipt of ultra-disperse structure.

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